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Evaluation and optimization of the bonding behavior between substrate and coating processed by laser cladding

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Abstract

The laser cladding process can be found in many different industrial applications. A lot of different material combinations were observed in recent years. For the application of laser cladded coatings in highly loaded areas, such as forming tool surfaces, the bonding characteristics between substrate and coating have to be evaluated and optimized. A special testing device is developed to measure the adhesive tensile strength of standardized laser cladded samples. To improve mechanical properties of the coating system within the process window, process parameters are tested and optimized by applying the design of experiment method. Results are presented from an iron based and a nickel based coating material on two different steel substrates.

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Keywords: laser cladding; adhesive tensile strength; bonding; design of experiment method

1. Introduction

The laser cladding process is known under different nomenclatures like Laser Metal Deposition (LMD), Direct Metal Deposition (DMD), Selective Laser Cladding (SLC), Direct Laser Cladding (DLC), Laser Rapid Manufacturing (LRM) and some others. Regardless of different process variants, the main principle - using a laser beam to melt a welding filler material on a substrate under protective atmosphere - is common to all. By computerized numerical control coatings and different geometrical shapes can be achieved. Typical technical applications are the generative manufacturing or repairing of turbine blades (Toyserkani et al. 2005, p.19), medical applications such as manufacturing of implant structures (Kumar et al. 2014), wear protection layers for mining and oil field equipment and also tool components for pressure die casting (Nowotny et al. 2010) and forming

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applications (Behrens et al. 2014). The deep drawing process of advanced and ultra high strength steels in the automotive industry is challenging for the tooling components that produce car body parts. New tooling solutions are needed to meet the requirements regarding tool wear, tribological surface condition, short time of manufacturing, the possibilities of flexible design changes and a cost effective production. New approaches also need to rethink solutions offered by the conventional toolmaking, leading to new processes and innovative manufacturing techniques. A possible solution is offered by the laser cladding process for active tool surfaces in the field of sheet metal forming. Klocke et al. (2014) is showing concepts for deep drawing tools combining the laser cladding process with local geometrical optimizations of highly stressed surface areas. In addition to the tribological surface properties, the consideration of the mechanical properties of the laser coatings is inevitable in this special field of application because of the stress loads of the tool in partial areas of the drawing radius and the blank holder. To find the optimum parameter setting within the process window of such laser cladded coatings specific evaluation methods are needed to quantify the coatings properties for tooling applications. Witzel et al. (2011) focused on a relation between process parameters, the microstructure and the ultimate tensile strength (UTS) of laser cladded Inconel bulk material. Through this investigation a coherence between process parameters and UTS was shown. Also Köhler et al. (2012) showed the effects on fatigue strength of laser coated samples. Nevertheless, using this process as coating technology, with typical coating thicknesses of 0,5 – 3,0mm, it is also very important to look at the interface zone between coating and substrate. A special testing device was developed and built up in order to measure the quality attribute adhesive tensile strength. The measured adhesive tensile strength and hardness values of the coatings are defined as quality attributes by applying the design of experiment method.

2. Experimental Setup

2.1. Equipment

All welding samples are laser cladded on a Trumpf DMD 505 laser cell. This machine is equipped with a 3,2kW CO2 laser source and a powder feeder to apply the coating material which is typical gas atomized with a particle size between 50 – 150µm. Fig. 1 is showing the process principle and an example of a partially cladded 3D geometry.

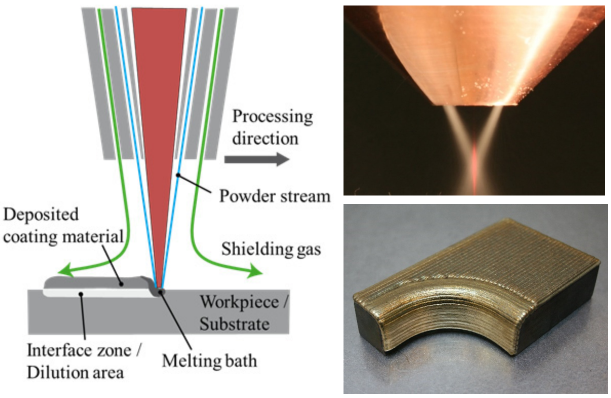

Fig. 1. Schematic process principle – laser cladding (left); welding optics (top right); tool surface coated with Cu85 (bottom right).

Tryouts of a new substrate/coating combination are done on a standardized flat sample as seen in Fig 2. Usually lines are welded at the beginning to find a first parameter set for a specific aspect ratio of the clad geometry. In a next step first areas are coated with different parameters in a single and multi-layer technique. This first steps are based on operator experience and the trial-and-error method. The main target in this phase is to eliminate typical failure modes like cracks, pores and the delamination defects of the coating. After a rough definition of the process window, further optimization can be done by welding samples with 12-areas with different parameter sets within the predefined process window. Depending on the number of observed parameters, a full or fractional factorial experimental design is chosen. Typically, every parameter set is welded with 3 repetitions. Since randomization is very important within DoE, the areas are laser cladded in random order.

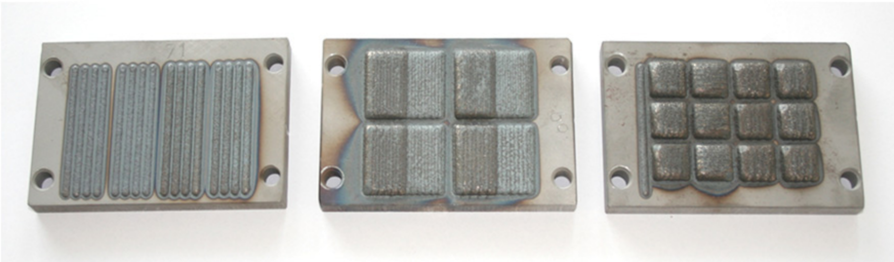

Fig. 2. Standardized specimens for line parameter test (left); 4-area single/multilayer test (middle); 12-area parameter test (right).

The designed test rig to measure the bonding strength is based on the experimental principle of Ollard who tested the adhesive strength of galvanic coatings (Kanani 2007). In the current setup a geometrical defined cross section in the interface zone between substrate and coating is set under tensile load until fracture. The principle is shown in Fig. 3. The geometrical shape is milled into the 12-areas specimen and each area is used for one tensile test. The maximum force is measured with a load cell.

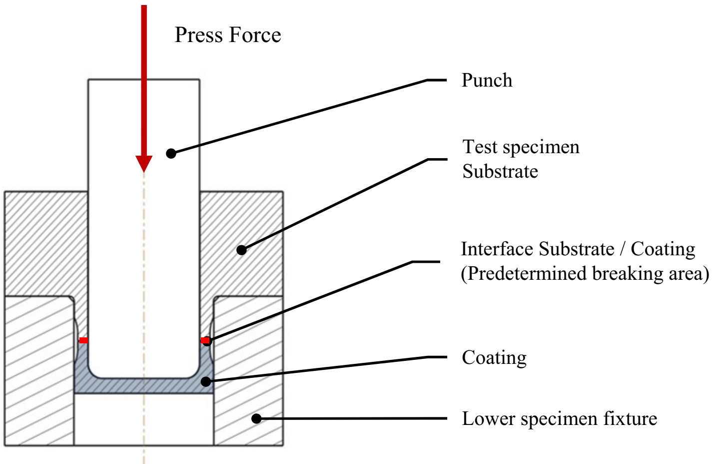

Fig. 3. Cross section of adhesive tensile strength test setup.

The crack initiation is rarely in the exact interface zone and more often nearby in the substrate or coating material area representing the weakest area in this zone. It is mainly influenced by factors like thermal residual stress, heat effected material damages and intermetallic phases because of dilution effects. The relationship between measured maximum tensile forces and the varied parameter settings are initially described by a linear phenomenological model. In this early phase there might be no physical understanding about the microstructure within the interface zone and diverse potential influences on it. Therefore, it is often designated as black box model. Nevertheless, it can help to find the physical correlation and interaction by carrying out further analysis.

Before the tensile test, the milled 12-area specimen is also used to undertake Vickers hardness measurements on the coating material side. The results are used to define a model between the hardness value and the parameter set.

2.2. Tested material combinations

The testing sequence was performed with two different substrate and coating materials. For the substrate steel, the materials 1.1730 (C45W) and 1.7131 (16MnCr5) are chosen. 1.1730 is very often used as the base material for plates, 1.7131 is a common used case hardening steel. For the coating materials, an iron based powder material Ferro55 and a nickel based material Ni25 are chosen. Both coating materials have a good hot working potential with a sound toughness and high resistance against tool wear. For the chemical composition see Table 1.

Table 1. Chemical composition of tested coating materials.

Designation	(weight-%)	C	Cr	Ni	Mo	Fe	Mn	Si	B
Ferro55	Iron base	0,50	7,00		2,50	balance	0,50	0,40	-
Ni25	Nickel base	<0,5	-	balance	-	<1,00	-	2,50	1,70

3. Process Parameter

Regarding the laser cladding process there are many process parameters influencing the quality attributes of the coating system. Fig. 4 is a clustered schematic diagram of possible factors.

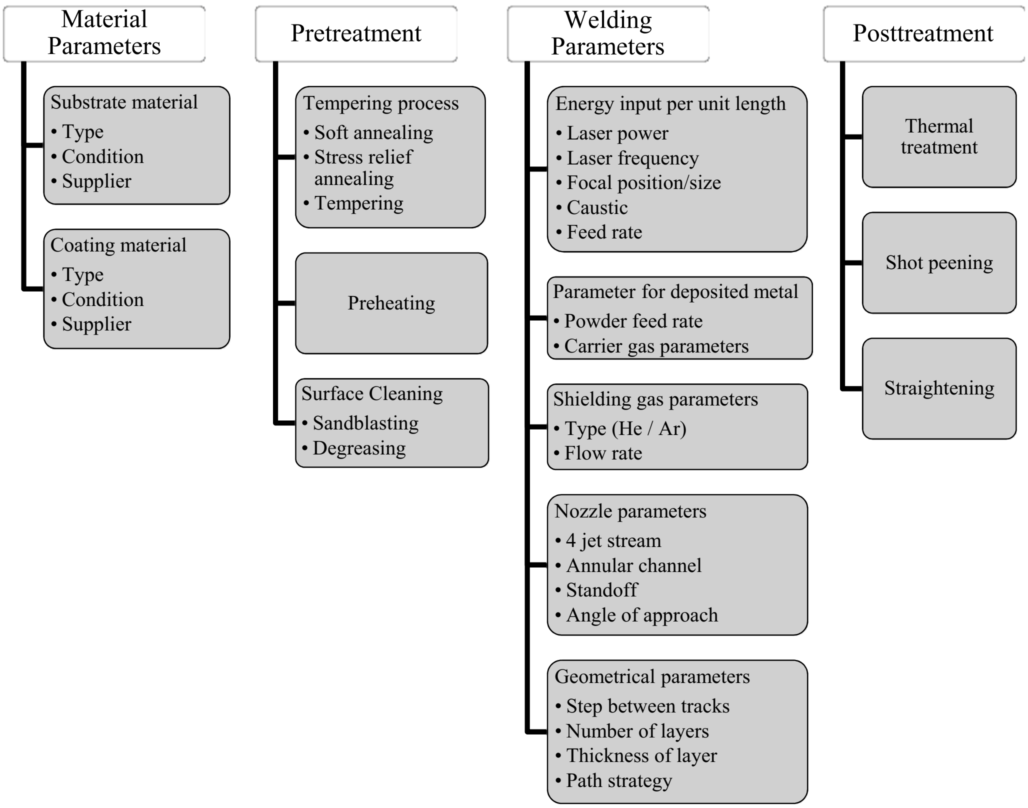

Fig. 4. LMD Parameters.

Many of the parameters are defined because of the material combination and the desired field of application of the coated parts. Some treatment is known to improve the coating quality, such as cleaning the surface before the cladding process. Nevertheless, a lot of parameters can be varied in a certain bandwidth. In the current case of coating development, many parameters are fixed after the preliminary tests. Further test sequences are performed by changing three to eight parameters on two stages. With an increasing number of varying parameters, a full factorial design of experiment is resulting in a high testing effort. This can be reduced by using fractional factorial designs with resolutions of IV or V. Table 2 presents typical varied parameters.

Table 2. Parameter and notation.

Parameter	Excel (Minitab) notation	Unit	Description
v	v	[mm/min]	Feed rate
T_{VW}	T_VW	[°C]	Preheating temperature
O_L	O_L	[%]	Track overlap factor
A_N	A_N	[%]	Aspect ratio
F_P	F_P	[g/min]	Powder feed rate
Δf_B	Δ f_B	[mm]	Focal shift
P_L	P_L	[W]	Laser power
f_L	f_L	[Hz]	Laser frequency

First trials with the Ferro55 coating material show a stable coating process based on welding parameters gained from experience. In a further step welding lines with different shapes were cladded and analyzed. Aspect ratios between height and width of a single track between 25% and 35% were chosen. A track overlap factor showed good results without pores and cracks independently from preheating the substrate. Based on this results an experimental matrix was defined, as shown in Table 3, for measuring hardness and bonding strength.

Table 3. Experimental matrix Ferro55 on 1.1730 / 1.7131, fractional factorial, 5 factors, 2 levels in 16 experiments with a resolution V.

Factors	**A**	**B**	**C**	**D**	**E**	**constant**	**constant**
Description	**v [mm/min]**	**O_L [%]**	**F_P [g/min]**	**T_{VW} [°C]**	**f_L [Hz]**	**P_L [W]**	**Δf_B [mm]**
Low	450	40	8	20	100	3200	5
High	600	60	10.5	250	5000		

Preliminary tests with Ni25 are performed similar to the iron based coating material. Laser pulsing with low excitation frequency showed no significant effect, so that it is set constant to the maximum possible value of 5000Hz. Therefore, the power density parameter is varied by shifting the laser focus between -5 and +5mm which results in laser spot sizes between Ø2.2 – Ø2.6mm. The experimental matrix is shown in Table 4.

Table 4. Experimental matrix Ni25 on 1.1730 / 1.7131, fractional factorial, 5 factors, 2 levels in 16 experiments with a resolution V.

Factors	**A**	**B**	**C**	**D**	**E**	**constant**	**constant**
Description	**v [mm/min]**	**O_L [%]**	**F_P [g/min]**	**T_{VW} [°C]**	**Δf_B [mm]**	**P_L [W]**	**f_L [Hz]**
Low	400	40	7.5	20	-5	3200	5000
High	600	60	9.25	250	+5		

Each parameter set is repeated three times in a randomized welding sequence. Only in terms of the preheating temperature, which is a difficult adjustable parameter, a clustering of experiments is carried out. All samples are clamped on a massive copper plate which has the possibility of temperature controlled heating.

4. Results

After welding with different parameters, a standardized specimen has 12 testing areas. The specimens are machined to their final shape by milling, drilling and grinding. After measuring the hardness of the coating the tensile test to evaluate the bonding strength is performed. Fig. 5 shows the specimen before and after testing.

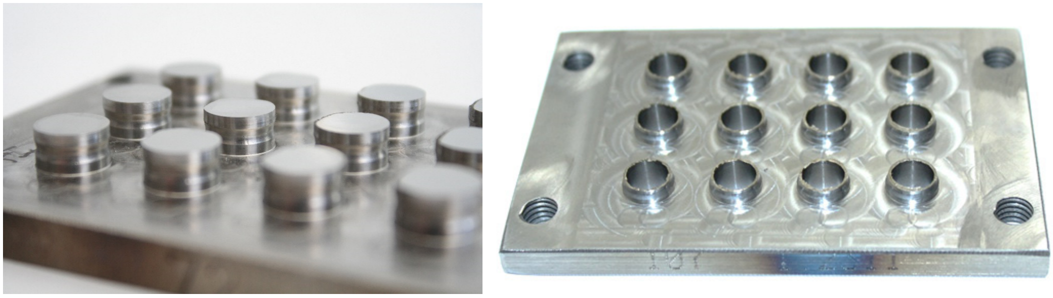

Fig. 5. 12-area specimen before (left) and after tensile testing (right).

4.1. Evaluation of Ferro55 on 1.1730 / 1.7131

4.1.1. Hardness of Ferro55

Looking at the results of hardness measuring on Ferro55 welded specimens it can be shown that there is a significant influence caused by different parameter settings as seen in Fig. 6. With a confidence interval of 90%, the following regression equation can be written.

$$\begin{aligned} Hardness\ [HV5] = {} & 667.0 + 0.066 \cdot v + 2.46 \cdot O_L - 4.99 \cdot F_P - 0.104 \cdot T_{VW} - 0.04359 \cdot f_L - \\ & -0.00606 \cdot v \cdot O_L + 0.000427 \cdot v \cdot T_{VW} + 0.000040 \cdot v \cdot f_L + 0.002948 \cdot F_P \cdot f_L - 0.000029 \cdot T_{VW} \cdot f_L \end{aligned} \tag{1}$$

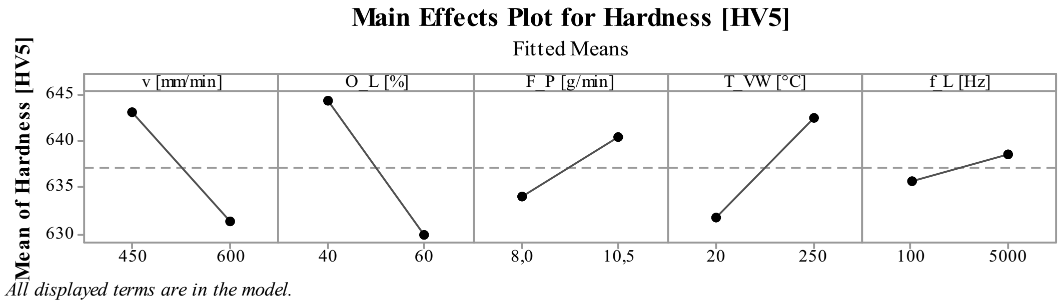

Fig. 6. Main effects of hardness - Ferro55.

Optimizing all welding parameters to a maximum hardness there is potential for increasing the hardness of about 10% which can lead to improvement regarding tool wear resistance. It is interesting that all parameter measures leading to a lower cooling rate, like increased preheating temperature, lower feed rate, higher track overlap for example are leading to a higher hardness of the coated material.

4.1.2. Ultimate adhesive strength of Ferro55

Looking at the results of the ultimate adhesive strength of the coatings the response of the quality attribute is displaying clear differences. The evaluation of the adhesive strength is not done with a tension value because it is impossible to reach uniaxial stress condition with the small specimen geometry. On this account the evaluation is done with the maximum tensile force.

Testing the coating material Ferro55 on the two different substrate materials the results show different effects represented in Fig. 7.

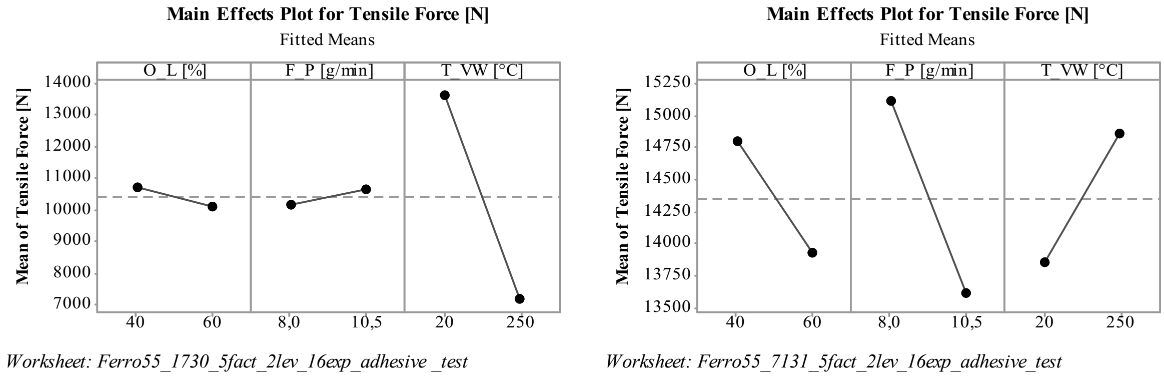

Fig. 7. Main effects of adhesive test Ferro 55 on substrate 1.1730 (left) and 1.7131 (right).

It seems that preheating the substrate 1.1730 to 250°C is causing a massive thermal damage to the coating system whereas preheating has a positive effect on the substrate 1.7131. The chosen confidence interval for this analysis is 95%. The potential of optimization between the worst and best parameter set is almost 100% for 1.1730 and almost 53% for 1.7131. Since the variation of settings is rather small there seems to be an important influence on the bonding strength of the coating.

4.2. Evaluation of Ni25 on 1.1730 / 1.7131

4.2.1. Hardness of Ni25

The nickel based coating Ni25 shows no significant trend. Looking at the boxplot of hardness (Fig. 8) there might be a slight decrease with higher preheating temperatures.

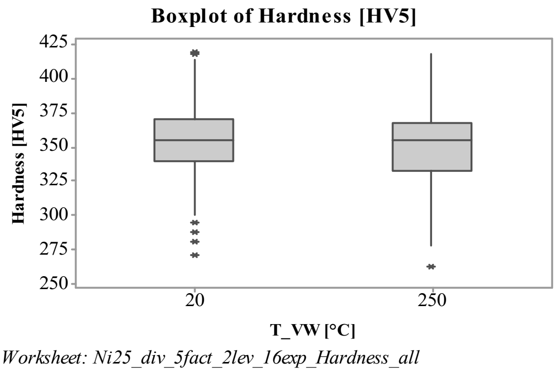

Fig. 8. Boxplot of Hardness – Ni25 in dependency of the preheating temperature.

4.2.2. Ultimate adhesive strength of Ni25

Welding the test specimens with the nickel based Ni25 coating it was experienced that there is a higher risk of crack formation without preheating the material. For this reason all gained values without preheating are not taken into account. Fig. 9 shows a clear difference of both the tested substrates. It seems that the combination Ni25/1.7131 is not favorable as coating system whereas a good bonding strength on 1.1730 can be realized by choosing a high feed rate and a low track overlap factor.

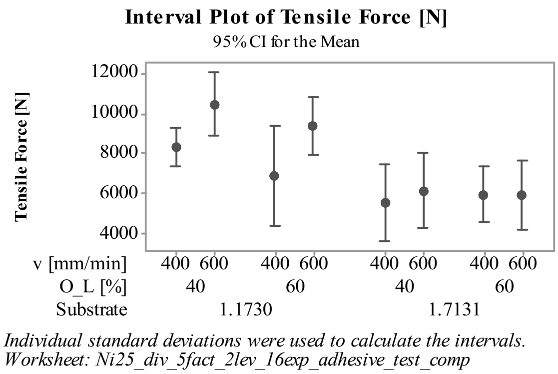

Fig. 9. Maximum tensile force of Ni25 and the substrates 1.1730/1.7131 as result of the parameters feed rate and track overlap factor.

It is also interesting when comparing both tested coating materials that the adhesive strength is strongly influenced by the chosen substrate material. Beside of the potential of optimization of one material combination it is clear that Ferro55 (coating)/1.7131 (substrate) and Ni25(coating)/1.1730 (substrate) seem to be the better choices of all tested combinations.

5. Summary and Outlook

The present paper describes one possible approach for the optimization of laser cladded coatings. Even though the LMD process has been industrially applied for some years now, the used coating systems and material combinations are mostly limited to variants that have been determined and validated by trial-and-error-methods. Common validation techniques, such as crack detection, measurement of hardness and the evaluation of micro-sections, are often inadequate when it comes to high mechanical requirements. This is why, one focus of this research was the development of new standardized evaluation methods to optimize LMD layers. As shown in the results of this paper several factors have different impact on quality attributes by testing different material combinations. One very useful tool was the measurement of the adhesive strength between the coating and the substrate material, as it is an unproblematic quantitative assessment of different coating systems or material combinations. The obtained results can be used to make the fundamental decision whether to use a defined material pairing or not. Further, the same results can be utilized to apply the principles of DoE and therefore optimize the coating parameters. New substrate-coating combinations can therefore be validated and enhanced effectively and fast. The optimization potential of the adhesive strength within a stable process window was found to be within a two to three digit percent range for all trials. This carries a tremendous potential for improvement of such coating systems. Nevertheless, this approach is rather a phenomenological descriptive model that does not account for the underlying physical mechanisms. The presented test procedure does, however, provide the possibility to explore this coherence in a target-oriented manner. The evaluation of the adhesive strength has been proven to be easily applied, while it delivers significant and stable results.

Acknowledgements

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